2022 DOE Vehicle Technologies Office Annual Merit Review
June 21, 2022

Simultaneous Greenhouse Gas and Criteria Pollutants Emissions Reduction for Off-Road Powertrains

Project ID: ACE171

DOE Contract # DE-EE0009873

Principle Investigator: Dr. James McCarthy, Jr.
Eaton

June 21, 2022

“This presentation does not contain any proprietary, confidential, or otherwise restricted information.”

Overview

Timeline

- Project start date: 2/1/2022
- Project end date: 5/1/2025
- Percent complete: Just Started

Barriers and Technical Targets

- Building high efficiency, off-road, future engine
  - Adding cylinder deactivation with transient controls and
  - Adding the high efficiency turbocharger with transient exhaust gas recirculation (EGR) pump controls.
- Validated operation in Budget Period 1

Budget

- Total project funding: $2,978,523
  - DOE share: $2,377,904
  - Contractor share: $600,619
- Funding for FY 2022
  - Budget Period 1: $1,550,378
  - (ending 4/30/2023)

Partners

EATON Powering Business Worldwide *James McCarthy, Jr.*

Testing
Vitaly Prikhodko Oak Ridge National Laboratory

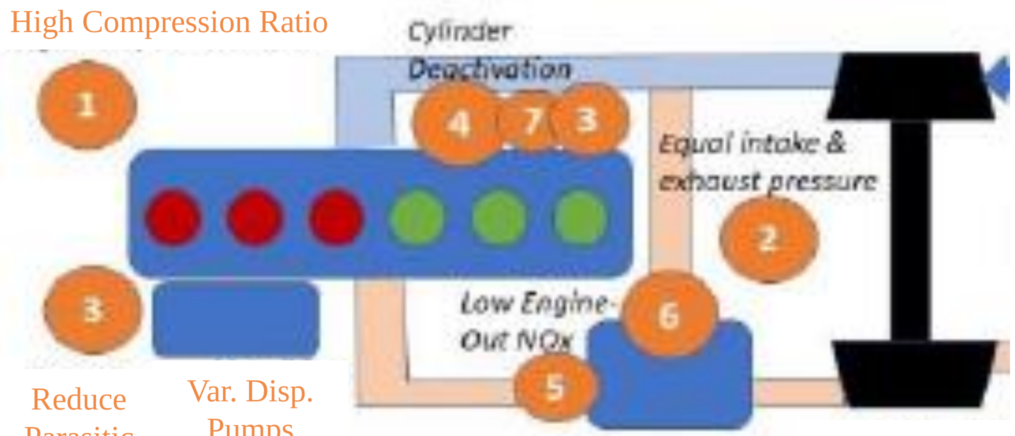
Engine
Fiat Powertrain *Ryan Bradley*

Aftertreatment
Tenneco
Southwest Research Institute

DOE Program: Future Engine & Aftertreatment

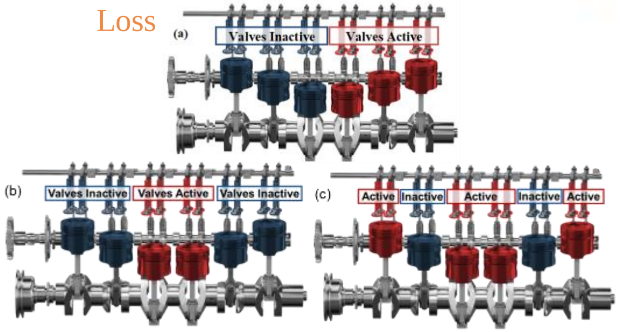
Off-Highway Engine of the Future

High Compression Ratio

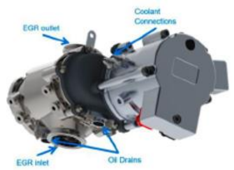


Reduce Parasitic Loss

Var. Disp. Pumps

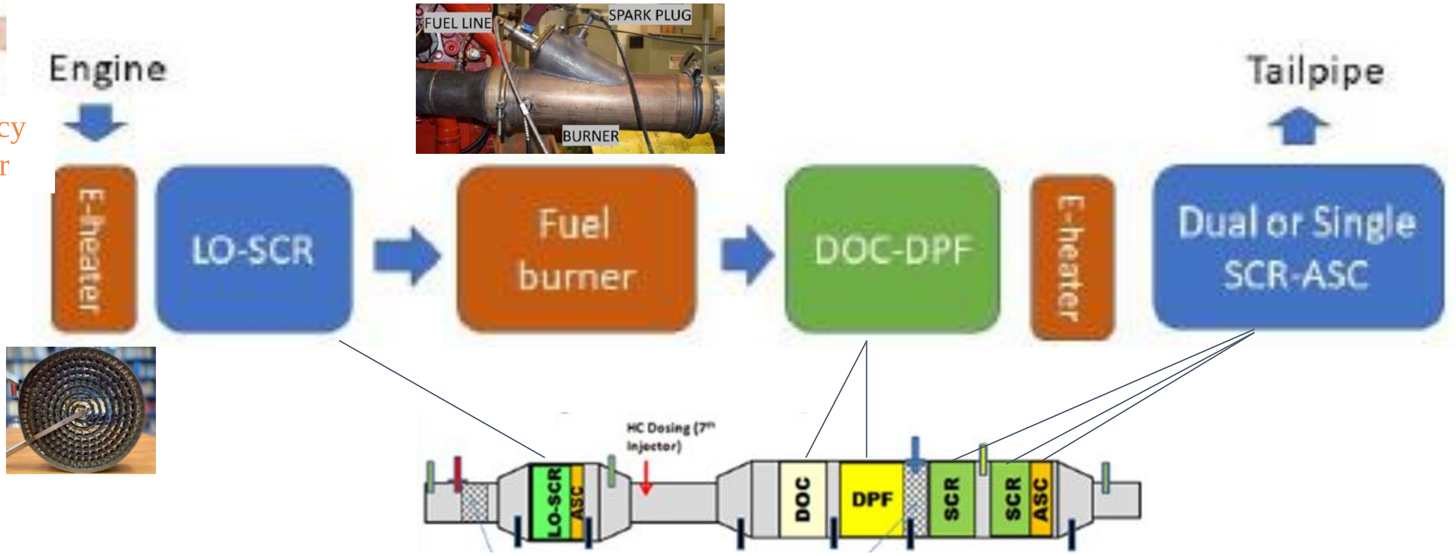


Low Power EGR Pump



High Efficiency Turbocharger

Modular Advanced Aftertreatment System

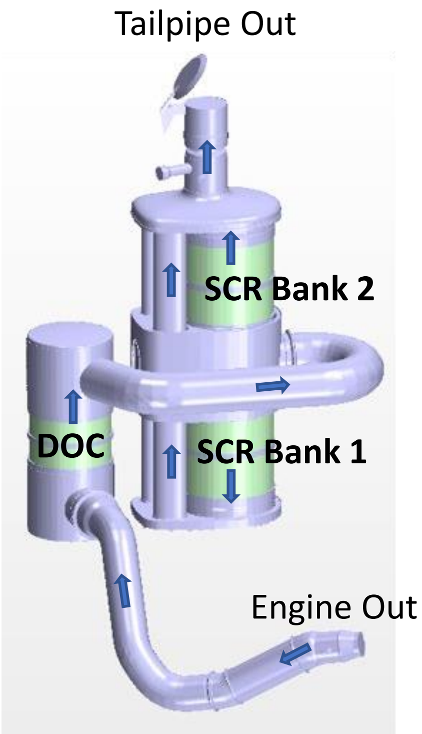


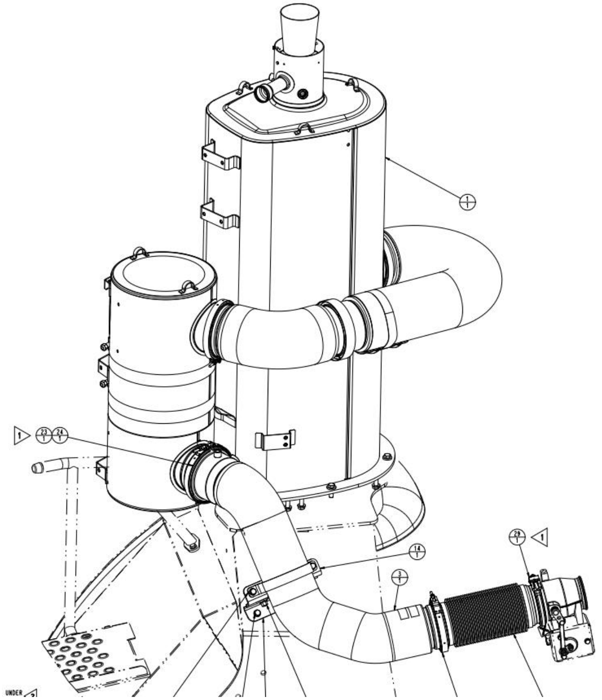
Future Testbed (Modular) is a Single Pass Aftertreatment System with a DPF

Baseline: Engine and Aftertreatment

FPT Cursor 13L Engine
407 kW @ 2100 rpm

Aftertreatment System is Flow Optimized for minimal backpressure and no Diesel Particulate Filter





Program Baseline: US Final Tier 4 Engine & Aftertreatment System

- Flow Optimized (minimized backpressure)
- No DPF (minimized backpressure)

Test Cycles and Evaluation Metrics

- Current Regulatory Cycles
  - Non-Road Transient Cycle
  - 8 Mode Cycle

Metric:	Today:	Program Deliverable:
NOx:	<0.4 g/kW-hr	<0.04 g/kW-hr (>90%)
GHG:	Needs to be measured	> 10% Reduction

- Tomorrows Regulatory Cycle
  - New Off-Highway Low Load Cycle

Program Deliverable:
Quantify NOx and GHG Reduction
(no current standard)
Characterize LLC between off-highway and on-road

- Field (in-use) Application Cycles
  - Cycles To be Determined in Budget Period 1
  - Candidates include:

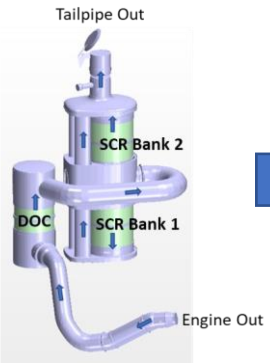
Table 1: Multiple Off-Road use-cases, duty cycles and emissions challenges		
Application	**In Use Cycle**	**GHG and NOx Challenges**
Heavy Tillage	High load cycle	Efficiency at max power is critical, while maintaining Exhaust Gas Recirculation (EGR) flow
Planting	Mix of loads with smooth transitions	Efficiency at multiple operating point
Scraper	High load cycle with transients	Multiple NOx spikes
Trailer Grain Cart	Low speed / low load cycle	Low exhaust temperature
Air seeder	Low and medium load	Insufficient heat in aftertreatment transients

Program Deliverable:
Quantify NOx and GHG Reduction
(no current standard)

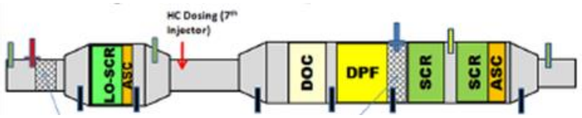
All Tests Conducted with Hydrothermal End of Life Aftertreatment Catalysts

Proposed Baseline Testing GHG Adjustment

- Measure NOx and GHG on all cycles
  - US Cursor 13L engine + MY2022 Production Aftertreatment (end of life hydrothermally aged)
- CFD Simulation Configurations
  - Configurations
    - Start with Final Tier 4 Aftertreatment (flow efficient path without a DPF)
    - Part 1: Configure Aftertreatment into Single Path
    - Part 2: Add DPF to Single Path
  - Operating Conditions (re-use same flows as those from final Tier 4)
    - Rated Speed (full load)
    - Max Power
  - Assessment
    - Part 1: Capture incremental backpressure impact for single path in terms of GHG
    - Part 2: Capture incremental backpressure impact for DPF in terms of GHG
    - Add two numbers together (Part 1 + Part 2)
    - Assumption: this delta is applied across all speeds and loads
  - GHG adjustment across cycles
    - Take measured GHG for each cycle baseline cycle (regulatory, new low load and field cycles) and correct with the CFD numbers for (1) single path and (2) added DPF.



GHG Correction for:
Single Path with DPF



GHG Reduction: Future Engine + Modular System Compared to GHG Adjustment for Baseline

This will represent a ~MY2024 Aftertreatment System with a DPF as our baseline

Strategies for Simultaneous NOx and GHG Reduction

Table 1: Key strategies to achieve 10% GHG reduction and 90% NOx reduction			
	Startegies	GHG benefit	NOx benefit
1	Increase compression ratio	2%	
2	Increase boosting / eliminate pumping losses	3%	
3	Reduce engine parasitic losses	2%	
4	Reduce engine displacement at low load	2%	<40%
5	Lower N20 formation (in Aftertreatment)	3.5%	
6	Lower engine-out NOx while minimizing pumping losses	-1%	33%
7	Aggressive exhaust and Aftertreatment thermal management (net)	0%	5%
8	Increase NOx conversion efficiency while minimizing incremental backpressure	-1%	85%
9	Functional re-use of technologies to achieve a system incremental cost <$4,000		

Table 8: NOx and CO2 testbeds reductions relative to State-of-Art and Tier 4b emissions				
	NOx reduction		GHG reduction	
Testbeds	**Engine**	**Aftertreatment**	**Engine**	**Aftertreatment**
Thermodynamics and parasitic loss	None	None	5%-7%	
EGR	25% to 35%		-1% to -2%	3.5% (from N20)
CDA	Up to 40%	Faster warmup	1% to 4%	
Aftertreatment		85%	-1%	
Heater / eng. controls			-1%	
Net (cycle dependent)	**90% (tailpipe)**		**6.5% - 12.5%**	

Greenhouse Gas (GHG) quantified in terms of CO_2

Detailed Program Scope

A. OBJECTIVES

Research, develop, & validate aftertreatment system-level strategies capable of ≥10% Greenhouse Gas (GHG) reduction and ≥90% Nitrogen Oxides (NOx) reduction for off-road powertrains over multiple duty cycles spanning the diverse applications in the segment, while maintaining affordability and robustness to ensure economic viability.

Simultaneous NOx & GHG Reduction

- 90% NOx Reduction
- 10% GHG Reduction

B. SCOPE OF WORK

The project will be conducted in 3 budget periods:

Budget Period 1: System Design and Testbeds Build: Define meaningful duty-cycles, baseline, and targets to ensure off-road segment coverage. Simulate, design, build, and validate the engine testbed and modular high conversion efficiency aftertreatment testbed.

Build & Baseline: Feb. 1, 2022 to May 1, 2023

- Baseline engine and Aftertreatment (AT) – at ORNL
- Future Engine Commissioned – at ORNL
    - Includes CDA & EGR pump systems
- Modular AT System Built and Aged – Delivered to ORNL

Budget Period 2: System Exploration and Optimization: Build prototype exhaust thermal management systems and new catalysis modules and incorporate in the modular aftertreatment. Build prototype high conversion efficiency elements and modular testbed allowing mix-and-match components to realize different architectures. Optimize multiple hardware architectures through controls and calibration on the testbeds. Explore and optimize architectures and predict optimum configuration.

Test: May 1, 2023 to May 1, 2024

- Characterize System Performance Using 5 Configurations
    - LO-SCR + Primary AT
    - Fuel Burner + Primary AT
    - LO-SCR + Fuel Burner + Primary AT
    - E-heater + LO-SCR + Primary AT
    - LO-SCR + DOC-DPF + E-heater + SCR

Budget Period 3: Limits of Performance Illustration: Build optimum configuration to achieve limits of performance and quantify that performance on testbeds.

Final Demo: May 1, 2024 to May 1, 2025

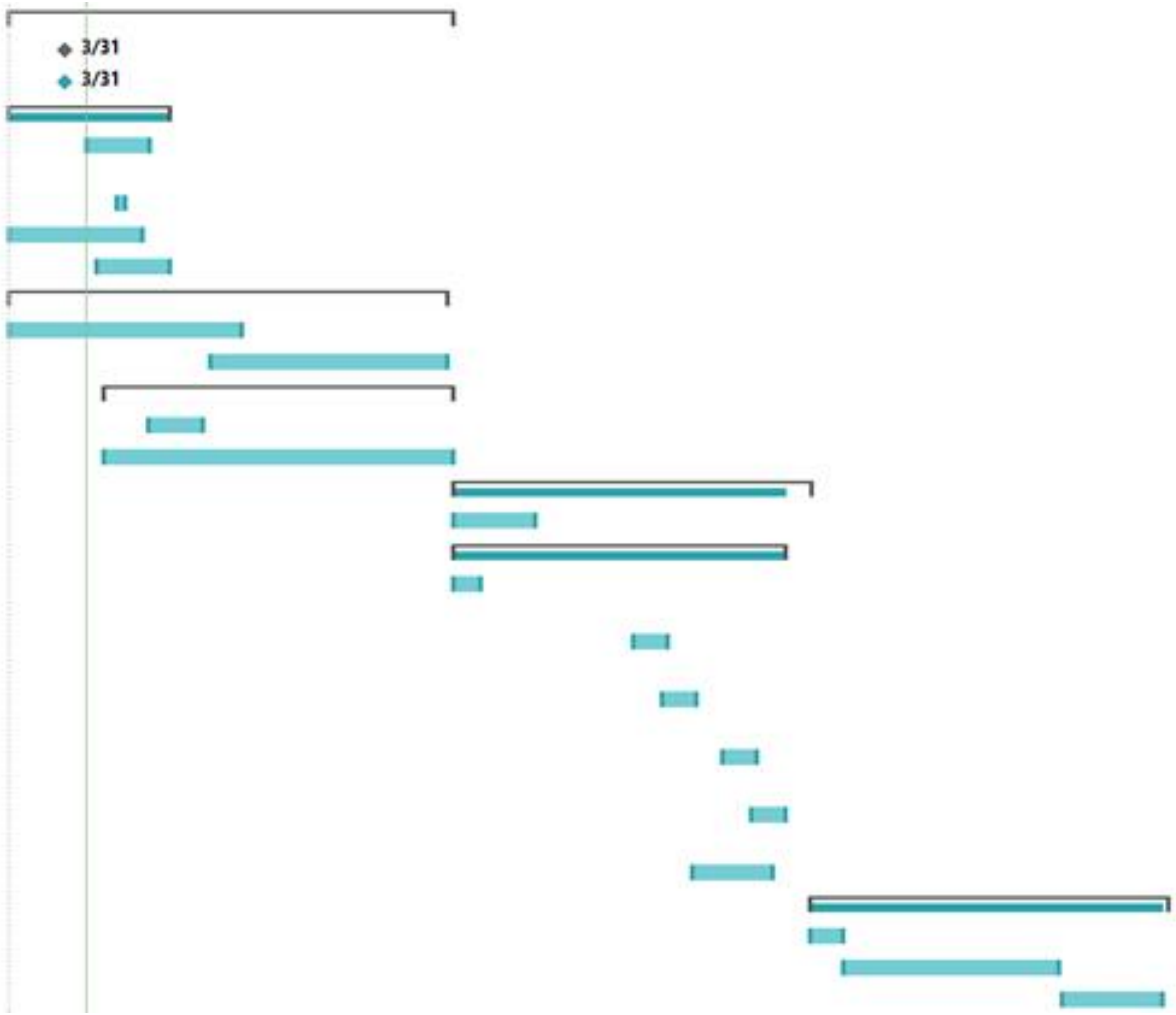
- Construct Final Configuration, Test and Quantify
- Final Report

Progress as of April 2022

Team Assembled, Baseline Configuration Agreed Upon and Project Management Plan Submitted

Program Schedule

Task	Start	Finish
Budget Period 1: System Design and Testbeds Build	Tue 2/1/22	Mon 5/1/23
Task 0.0 – Project Management and Planning:	Thu 3/31/22	Thu 3/31/22
Task 0.1 – Kick-Off Meeting:	Thu 3/31/22	Thu 3/31/22
Task 1.1 – State-of-Art System Definition and Performance Metrics	Tue 2/1/22	Fri 7/15/22
Subtask 1.1.1 - State-of-Art system definition: Create Cursor 13/Tier IVb baseline.	Fri 4/22/22	Fri 6/24/22
Subtask 1.1.2 - Develop duty cycle and GHG and Nox performance tar	Mon 5/23/22	Mon 5/30/22
Subtask 1.1.3 - Future engine and Aftertreatment concept and archite	Tue 2/1/22	Fri 6/17/22
Subtask 1.1.4 – Preliminary cost model	Mon 5/2/22	Fri 7/15/22
Task 1.2 – Future Engine Test Development	Tue 2/1/22	Tue 4/25/23
Subtask 1.2.1 – Design and fabricate future engine testbed:	Tue 2/1/22	Tue 9/27/22
Subtask 1.2.2 – Future engine testbed commissioned at ORNL:	Fri 8/26/22	Tue 4/25/23
Task 1.3 – Modular High Conversion Efficiency Aftertreatment Testbed	Mon 5/9/22	Mon 5/1/23
Subtask 1.3.1 – Baseline state-of-art engine + aftertreatment	Fri 6/24/22	Thu 8/18/22
Subtask 1.3.2 – Modular aftertreatment testbed commission	Mon 5/9/22	Mon 5/1/23
Budget Period 2: System Exploration and Optimization	Mon 5/1/23	Wed 5/1/24
Task 2.1 – System Integration:	Mon 5/1/23	Mon 7/24/23
Task 2.2 – System Exploration and Optimization:	Mon 5/1/23	Fri 4/5/24
Subtask 2.2.1 – Test Future Engine with Aftertreatment Configuration 1 — 1	Mon 5/1/23	Mon 5/29/23
Subtask 2.2.2 – Test Future Engine with Aftertreatment Configuration 2 — 2	Wed 11/1/23	Wed 12/6/23
Subtask 2.2.2 – Test Future Engine with Aftertreatment Configuration 3 — 3	Fri 12/1/23	Fri 1/5/24
Subtask 2.2.2 – Test Future Engine with Aftertreatment Configuration 4 — 4	Thu 2/1/24	Thu 3/7/24
Subtask 2.2.2 – Test Future Engine with Aftertreatment Configuration 5 — 5	Fri 3/1/24	Fri 4/5/24
Task 2.3 – Trade-Off Analysis and Limits of Performance Analysis	Mon 1/1/24	Fri 3/22/24
Budget Period 3: Limits of Performance Illustration	Wed 5/1/24	Thu 5/1/25
Task 3.1 – System Integration:	Wed 5/1/24	Mon 6/3/24
Task 3.2 – Performance Measurement:	Mon 6/3/24	Fri 1/10/25
Final DOE Report — 6	Mon 1/13/25	Fri 4/25/25



Publication Plan: 6-7 Journal Papers at the end of each major test. Plus, comparison of the LLC between off-highway and on-highway

Summary

- Team is Assembled
- Baseline Configuration Agreed Upon
  - US Final Tier 4 Engine and Aftertreatment
- Greenhouse Gas Correction Agreed Upon
  - CFD to correct baseline → single path aftertreatment with DPF
- Project Management Plan Submitted
- Program Schedule Created
- Publication Plan Established